In-Plane Experimental Testing of Timber-Concrete Composite Floor Diaphragms

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ABSTRACT: Recent advances in the design of multi-storey timber buildings have led to viable structural systems that allow open floor plans with large spans between frames and/or walls. Timber-concrete composite (TCC) flooring can achieve the spans required but have the potential to be flexible under diaphragm actions, which can significantly alter the seismic response of a building.

In-plane experimental tests on a one-third scale TCC floor were performed using quasi-static earthquake loading simulation. The experimental results indicate that the deformation between the floor and lateral load resisting systems (LLRS) is much greater than the in plane deformation of the floor diaphragm itself for the square aspect ratio considered. Hence, a floor system with similar aspect ratio can be modelled as a single-degree-of-freedom for future structural analyses.

Different diaphragm connections were considered between the floor unit and lateral restraints, which simulate the lateral load resisting system. The connection was either timber-to-timber or concrete-to-timber, incorporated screws or nails acting as dowels or inclined at 45 degrees. Each connection type performed differently in terms of stiffness, strength, ductility capacity and induced damage. Screws that were orientated at 45 degrees to the connection interface were significantly stiffer than fasteners aligned orthogonal to the interface. There was little difference in the initial stiffness for the concrete-to-timber connection compared to the timber-to-timber connection. The testing indicated that a timber-to-timber interface is more desirable because of construction ease and reparability.

1 INTRODUCTION

New forms of multi-storey timber buildings are being developed at the University of Canterbury, University of Auckland and the University of Technology Sydney under the Structural Timber Innovation Company Ltd (STIC). These building systems incorporate large timber sections, constructed of Laminated Veneer Lumber (LVL), connected by steel post-tensioning tendons (Palermo et al., 2005). These buildings have the potential to compete with current forms of construction in concrete and steel (Smith et al., 2008) and can provide open floor plans which are suitable for commercial or office type structures.

To achieve the long floor spans required, Timber-Concrete Composite (TCC) floor systems have been developed (Łukaszewska et al., 2008). To date there has been little research into the performance of TCC floors acting as a diaphragm or the performance of the diaphragm connection to the lateral load resisting system (LLRS). The connection details could prove crucial to the effectiveness of the floor
units under seismic loads.

The in-plane stiffness of the TCC diaphragm is a combination of the flexural and shear deformation of the floor unit and the deformation of the connectors between the floor unit and the LLRS (Brignola et al., 2008). For similar systems in precast concrete, no distinction is typically made between the deformation of the connectors and the deformation of the diaphragm (Fleischman and Farrow, 2001; Lee et al., 2007; Nakaki, 2000). Instead, an over-all effective flexural stiffness is used that takes into account cracking of the concrete and the deformation of the discrete connections between floor units. While for some types of concrete diaphragms this may be reasonable, for TCC floor units it is possible that the most significant deformation component comes from the discrete connectors between the LLRS and the diaphragm. If this is the case, the structural response of the floor could be simplified to a single degree of freedom (SDOF) system. This would have implications for the expected peak floor accelerations and displacements during an earthquake.

During the 1994 Northridge earthquake several structures collapsed due to larger than expected floor diaphragm forces (Hall, 1995) and high drift demands on gravity systems (Iverson and Hawkins, 1994). The higher mode response of structures with flexible floor diaphragms results in an amplification of the peak floor accelerations above the peak ground acceleration (Rodriguez et al., 2002), often in excess of the design values predicted by international design codes (FEMA, 450; IBC, 2003; UBC, 1997). The flexibility of the diaphragm can also amplify the interstorey drift demands on gravity systems (Fleischman and Farrow, 2001). Amplification of floor accelerations and interstorey drifts can depend on both the stiffness of the LLRS and the diaphragm stiffness.

The overall objective of this research is to determine if diaphragm flexibility should be considered in the design of post-tensioned timber buildings and establish which type of structural systems, if any, could be susceptible to increased floor accelerations and interstorey drift demands. Conversely, it may be more cost effective to consider the flexibility of the diaphragms in design as it can result in lower demands for the LLRS (Nakaki, 2000). This research will be concluded in subsequent companion papers (Newcombe et al., 2009) currently in preparation.

This paper describes the experimental testing of a TCC floor diaphragm at the University of Canterbury. The deformation components of the floor unit are examined to determine the relative contribution from the diaphragm and the connectors. Different connection arrangements were tested between the floor unit and lateral restraints (which simulate the LLRS), each with different structural performance.

2 EXPERIMENTAL TESTING OF TCC DIAPHRAGM

2.1 Test specimen

To investigate the effectiveness of TCC floor units acting as diaphragms, a reduced scale floor unit was constructed. The diaphragm subassembly was approximately a 1/3 scale model of a hypothetical 8m by 8m floor unit, as shown in Figure 1a, designed for office type gravity loading.

Figure 1b and c provide a depiction of the scaled down floor unit and its associated testing apparatus. The floor subassemblage was 3m by 3m in plan, incorporated a 25mm low shrinkage concrete slab, reduced scale reinforcing mesh, 7mm permanent plywood formwork, 150x45mm LVL joists spaced at 500mm centres and two 250x153mm transverse gravity beams.

The floor joists include TCC connectors designed according to Yeoh et al (2008). Ten notches were machined into each joist and two 5.3x80mm coach screws were positioned in the centre of the notch, providing a high degree of composite action between the LVL joists and the concrete slab. At each end the joists were connected to the primary gravity beams, which also had notched slab connections. The floor unit rested on timber corbels which, in the prototype structure, would be connected to the face of the columns.
2.2 Floor connection details

Five different diaphragm connection arrangements were investigated, as described in Figure 2 and Table 1. The connections consisted of either screws or nails, acting as dowels or inclined at 45 degrees to the connection interface. One end of the fasteners was embedded in the timber lateral restraining beam and the other was cemented into the concrete slab or connected to a timber joist.

The number of fasteners was determined by considering the inertial forces at the top floor of a full scale 6-storey post-tensioned timber prototype building designed according to displacement-based design approach (Newcombe, 2008) and amplified according to Bull et al (1997). The connection strength was estimated by using Eurocode 5 (EC5, 1994) for orthogonal fasteners, Kavaliauskas et al (2007) for inclined fasteners within concrete and Betjka et al (2002) for inclined fasteners within timber. However, these references did not provide design information for cyclic loading or for inclined fasteners under compression.

2.3 Test setup and loading protocol

The seismic inertial forces were approximated in the experiment by using a 2-point loading arrangement as shown in Figure 1b. The loading was symmetric about the floor centreline with a distance of 1/3rd the width of the floor between each point load.

A displacement controlled quasi-static loading protocol was applied to the floor as specified by ISO (2007). Although the protocol is usually applied to shear walls, it is well suited to this type of diaphragm test. Displacement amplitudes are defined by the expected displacement at maximum force; each level of displacement amplitude undergoes 3 cycles (to capture strength degradation) and then is increased by 20%. The alternative standard (CEN, 2001), while very similar to ISO (2007), is less demanding at lower cycles and requires the yield displacement to be predicted, which is often difficult to quantify.

![Figure 1. a) Plan view of prototype structure b) 3-D view of floor subassembly without concrete c) Plan view of floor subassembly](image-url)
Figure 2. Five floor connection arrangements

Table 1. Diaphragm connection characteristics

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Connection interface</th>
<th>Fasteners</th>
<th>Size (mm)</th>
<th>Number of fasteners</th>
<th>Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>Timber-to-concrete</td>
<td>Screws</td>
<td>Ø5.3 – 75</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Test 2</td>
<td>Timber-to-concrete</td>
<td>Screws</td>
<td>Ø5.3 – 100</td>
<td>12</td>
<td>45</td>
</tr>
<tr>
<td>Test 3</td>
<td>Timber-to-timber</td>
<td>Screws</td>
<td>Ø5.3 – 125</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Test 4</td>
<td>Timber-to-timber</td>
<td>Nails</td>
<td>Ø5.3 – 125</td>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td>Test 5</td>
<td>Timber-to-timber</td>
<td>Screws</td>
<td>Ø5.3 – 150</td>
<td>12</td>
<td>45</td>
</tr>
<tr>
<td>Test 6</td>
<td>Diaphragm test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 TEST RESULTS AND COMPARISON

3.1 Stiffness of the diaphragm and its connectors

The relative stiffness of the diaphragm and its connectors has implications on the seismic response of a building and effects how the floor system can be modelled (Brignola et al., 2008). If the diaphragm is effectively rigid, a SDOF representation of the floor is an adequate model for seismic analysis.

During testing, the deformation of the diaphragm and the connectors was recorded. Table 2 shows the ratio of the diaphragm displacement and connector displacement recorded at the peak force. The diaphragm displacement in most cases was less than 5% of the total displacement. For tests 1 and 2, imprecise experimental measurements and twisting of the floor unit may have affected the relative displacement of the diaphragm.

For Test 6, movement was prevented between the lateral restraining beam and the floor unit to give a more direct indication of the stiffness of the floor diaphragm. The experimental results indicated that the initial uncracked stiffness of the diaphragm was approximately 3000 kN/mm and the cracked stiffness was 300kN/mm. The stiffest connection had an initial stiffness of 80 kN/mm, which is much less than the stiffness of the diaphragm.

Using classical beam theory to estimate the floor displacements demonstrates that shear deformation is much more significant than flexural deformation. The theoretical stiffness of the diaphragm acting as a beam is 1500 kN/mm, which compares reasonably well with the measured initial uncracked stiffness of 3000kN/mm, given the accuracy of the instrumentation at such small displacements. The cracked stiffness is roughly 20% of the theoretical elastic stiffness.
Table 2. Deformation of the floor diaphragm (Δ_{dia}) and diaphragm connectors (Δ_{con}) at peak resistance

<table>
<thead>
<tr>
<th>Test Name:</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_{max} (kN)</td>
<td>37</td>
<td>79</td>
<td>46</td>
<td>78</td>
<td>61</td>
</tr>
<tr>
<td>Δ_{dia} (mm)</td>
<td>0.21</td>
<td>0.21</td>
<td>0.02</td>
<td>0.14</td>
<td>0.03</td>
</tr>
<tr>
<td>Δ_{con} (mm)</td>
<td>3.00</td>
<td>1.84</td>
<td>4.81</td>
<td>8.92</td>
<td>1.51</td>
</tr>
<tr>
<td>Δ_{dia}/(Δ_{dia}+Δ_{con}) (%)</td>
<td>6.4</td>
<td>10.2</td>
<td>0.5</td>
<td>1.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

3.2 Hysteretic response

To examine the efficiency of each type of floor connection the hysteretic response is considered, as shown in Figure 3, in terms of average connector displacement and total force applied to the diaphragm. In Figure 3f, the normalized backbone curves of each test are provided for comparison. The force ordinate is normalized according to the number of fasteners in each test.

Considering all tests, inclined fasteners produced the stiffest connections. There was little difference in stiffness between inclined fasteners that were embedded within the concrete slab (Test 2) or the timber joist (Test 5). For both the concrete-to-timber and timber-to-timber connections, the inclined screws provide roughly four times the stiffness of orthogonal screws. The nailed connection (Test 4) had the lowest initial stiffness but allowed the largest diaphragm displacements before failure. In addition, the nailed connection was more flexible than equivalent screwed connection (Test 3). It is likely that this is due to a lower grade of steel for the nails.

The peak strength for each test (see Table 2) varied between 37 and 79kN. When the peak strength is normalised (see Figure 3f), it is evident that there is significantly higher strength for inclined versus orthogonal fasteners in concrete but little difference for timber. This indicates that in concrete the inclined fasteners are active in both compression and tension, providing more strength per fastener than a dowel fastener. For timber-to-timber connections, it appears that fasteners are less effective in compression than in tension. The peak strength provided by the inclined fasteners in concrete is 30% higher than inclined fasteners in timber. In addition, inclined screws in concrete achieved roughly twice the strength of orthogonal screws in concrete. By changing the orientation of the screws from orthogonal to inclined, the failure mechanism was altered from hinging within the timber restraining beam to crushing in the concrete slab respectively. For each test, there were residual friction forces of between 10 to 20kN once the fasteners had failed.

3.3 Damage mechanisms and limit states

Each type of connection produced different levels of damage and ductility capacity, as shown in Table 3. The cracking, yield and ultimate displacement normalized by the yield displacement are listed for each test. Obviously, only the concrete connections had the potential to crack. The ultimate point was defined by the displacement reached when the backbone curve degraded to 80% of the peak force.

Inclined screws within concrete were the most ductile type of connection; although the strength degraded at relatively small displacements (approx. 6mm), the yield displacement was small due to the high initial stiffness. Yet the failure mechanism was extensive cracking of the concrete slab (see Figure 4a), which would result in costly repairs. In contrast, at a displacement of 13mm, nailed connections achieved roughly half the ductility capacity of the inclined screws. However, the failure mechanism of the timber-to-timber connections results in much less damage than the concrete-to-timber connections (see Figure 4b). For timber-to-timber connections, if repair is needed after an earthquake, it is a simple matter of adding fasteners adjacent to the original failed fasteners.

For the concrete-to-timber connectors, the inclined screws (Test 2) failed by concrete crushing while the orthogonal screws developed plastic hinges within the timber. It is noted that full-scale connections may not have analogous failure mechanisms to the reduced scale model.
Figure 3. Hysteretic response of Tests 1 to Test 5

Figure 4. Damage a) Inclined screws in concrete (Test 2) b) Orthogonal screws in timber (Test 3)

Table 3. Damage mechanisms and limit states in terms of the cracking displacement ($\Delta_{cr}$), yielding displacement ($\Delta_y$) and ultimate displacement ($\Delta_u$)
<table>
<thead>
<tr>
<th>Test Name</th>
<th>$\Delta_cr$ (mm)</th>
<th>$\Delta_y$ (mm)</th>
<th>$\Delta_u$ (mm)</th>
<th>$\Delta_cr/\Delta_y$</th>
<th>$\Delta_u/\Delta_y$</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>-</td>
<td>1.3</td>
<td>5.5</td>
<td>-</td>
<td>4.2</td>
<td>Cracking did not occur, failure due to hinging in the timber.</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.6</td>
<td>0.6</td>
<td>6.4</td>
<td>1.0</td>
<td>10.7</td>
<td>Yielding and cracking is due to the loss of mechanical anchorage in the concrete.</td>
</tr>
<tr>
<td>Test 3</td>
<td>-</td>
<td>1.1</td>
<td>7.0</td>
<td>-</td>
<td>6.4</td>
<td>Double hinging within the timber.</td>
</tr>
<tr>
<td>Test 4</td>
<td>-</td>
<td>1.6</td>
<td>13.0</td>
<td>-</td>
<td>8.1</td>
<td>Double hinging within the timber.</td>
</tr>
<tr>
<td>Test 5</td>
<td>-</td>
<td>1.1</td>
<td>4.5</td>
<td>-</td>
<td>4.1</td>
<td>Both double hinging and pull out occurred within the timber.</td>
</tr>
</tbody>
</table>

4 CONCLUDING REMARKS

Several alternative diaphragm connections for post-tensioned timber buildings with TCC floors have been developed and tested under in-plane cyclic loading. The following conclusions are drawn from the floor diaphragm testing:

1. Inclined fastener connections provided approximately four times the stiffness of dowel fasteners.

2. There are minor differences in terms of in-plane stiffness between concrete-to-timber and timber-to-timber connections. However, the nailed timber-to-timber connections were less stiff than connections using screws.

3. There is little increase in the peak strength (per fastener) using inclined instead of orthogonal fasteners in timber-to-timber connections. Yet for concrete-to-timber connections, changing the orientation of the fastener from orthogonal to inclined, caused the failure mechanism to change to concrete crushing rather than hinging of the fastener within the timber, resulting in higher strength.

4. Inclined screws in concrete-to-timber connections produced the highest ductility capacity. However, concrete-to-timber connections can result in extensive cracking of the concrete if they are overloaded during an earthquake, resulting in costly repairs. Inclined screws in timber-to-timber connections achieved 70% of the strength of the concrete equivalent and were easily replaced, repaired, or retrofitted.

5. The diaphragm deformation was predominantly due to shear strain. The initial stiffness predicted by standard beam theory was reasonably close when compared to the experimental results. After cracking, the stiffness of the diaphragm was 20% of the theoretical elastic stiffness.

6. The deformation of the concrete diaphragm was negligible compared to the deformation of the connectors. Hence, the concrete diaphragm can be modelled as a rigid unit or as a SDOF system in a two dimensional seismic analysis of a building. Therefore, TCC floor diaphragms of similar or smaller aspect ratios can be reasonably represented as SDOF systems for modelling floor flexibility. This is a significant simplification for future investigations, which aim to quantify the effects of floor flexibility on the dynamic response of post-tensioned timber buildings. Sensitivity studies on effects of varying floor aspect ratios are required to determine when this simplification is appropriate. These studies are the focus of on going study.
REFERENCES:


